

# Carbon sequestration of modern *Quercus suber* L. silvoarable agroforestry systems in Portugal: a YieldSAFE-based estimation

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**Abstract** Modern alley cropping designs, with trees aligned in rows and adapted to operating farming machinery, have been suggested for Europe. This paper explores the potential for adoption of cork oak (*Quercus suber* L.) agroforestry in Portugal and estimates the potential carbon sequestration. Spatial modeling and Portuguese datasets were used to estimate target areas where cork oak could grow on farmland. Different implementation scenarios were then modeled for this area assuming a modern silvoarable agroforestry system (113 trees ha<sup>-1</sup> thinned at year 20 for establishing 50 trees ha<sup>-1</sup>). The YieldSAFE process-based model was used to predict the biomass and carbon yield of cork oak under low and high soil water holding capacity levels. Approximately 353,000 ha are available in Portugal for new cork oak alley cropping. Assuming implementation rates between 10 % of the area with low soil water capacity (60 mm: 15 cm depth, coarse texture) and 70 % of the area with high soil water holding capacity (1,228 mm: 200 cm depth, very fine texture), then carbon sequestration could be  $5 \times 10^6$  and  $123 \times 10^6$  Mg CO<sub>2</sub> respectively. Due to higher yields on more productive land, scenarios of limited

implementation in high productivity locations can sequester similar amounts of carbon as wide implementation on low productivity land, suggesting that a priori land classification assessments can improve the targeting of land and financial incentives for carbon sequestration.

**Keywords** Land use change · Agricultural land · Montado · Dehesa · Alley cropping · Modeling

## Introduction

The main agroforestry tree species in Portugal are cork oak (*Quercus suber* L.) and holm oak (*Quercus rotundifolia* L.). These species cover 716,000 and 413,000 ha respectively, accordingly to the National Forest Inventory (NFI). They account for 30 % of the total carbon (C) present in Portuguese forests, with cork oak storing  $64 \times 10^6$  Mg CO<sub>2</sub> and holm oak storing  $20 \times 10^6$  Mg CO<sub>2</sub> (AFN 2010).

The traditional agroforestry systems are characterized by scattered trees. However alternative modern silvoarable agroforestry (SAF) systems can have spatially organized tree rows to facilitate the use of farm machinery (Dupraz et al. 2005; Liagre and Dupraz 2008). In a Pan-European context, the support for establishing new agroforestry systems was, for the first time, explicit in the European Union Regulations (EC 2005) and is continued in the Common Agricultural Policy for 2014–2020 (EC 2013). In Portugal, the

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regulation has been transposed under the Portaria 1137-B/2008 and the Despacho 8488-B/2011 (DR 2008, 2011), and it supports the establishment of new agroforestry systems.

The above regulation and the *Quioto protocol* commitments, which identified a carbon sequestration deficit in new afforestation areas in 2010 of about  $2,739 \times 10^3$  Mg CO<sub>2</sub> (MAODTR 2012), provide an opportunity for silvoarable agroforestry. Hence this paper explores the potential of carbon sequestration under modern cork oak alley cropping systems on agricultural land by integrating geographical information systems with tree growth modelling. The research had three phases: (1) estimation of target areas where new agroforestry plantations could be developed, (2) calibration of a process-based model to estimate cork oak biomass growth, and (3) analysis of implementation scenarios to determine the potential carbon sequestration.

## Materials and methods

Estimation of target areas where new agroforestry plantations could be developed

In order to identify target areas to plant cork oak on agricultural land, we gathered information on the distribution of farmland, and potential cork oak tree distribution. Available agricultural land was retrieved with Geographic Information Systems (GIS) by extracting the rainfed “arable land” class from the Corine dataset (CLC 2000).

The autecology of cork oak is well established but there is a lack of consensual and consistency on distribution maps (e.g. APA 1984; EUFORGEN 2009; Natividade 1950). Most of the available maps are hand drawn, based on expert knowledge, coarse scaled, or lack a description of the method used. To overcome these problems, a map of the potential cork oak distribution was prepared based on literature thresholds (APA 1984; Correia and Oliveira 2003; Natividade 1950; Oliver 1980). Focusing on cork production, the environmental thresholds for tree growth distribution were: (1) altitude lower than 600 m (APA 1982), (2) annual precipitation greater than 600 mm (APA 1974a), (3) mean annual temperature of 16–19 °C (APA 1974b) and (4) pH of 4.6–7.3 (APA 1979). Each of these criteria was met for a potential cork oak distribution map created using ESRI ArcGIS© 10. The

combination of the available arable land and the potential tree distribution was used to delineate the target areas for cork oak agroforestry systems.

YieldSAFE calibration and validation to predict biomass growth

YieldSAFE is a process-based parameter-sparse dynamic model for predicting resource capture, growth, and production in agroforestry systems (van der Werf et al. 2007). We selected this model because of its simplicity and capacity to model resource (water and light) capture and competition by tree stands, and the possibility of using different climate scenarios which was not possible with existing empirical models such as SUBER (Tomé 2004).

However YieldSAFE has not been previously calibrated and validated for cork oak. The calibration and validation was made using dominant height curves proposed by Sanchez-Gonzalez et al. (2005) and the following existing data sets:

1. annual dbh growth measurements (unit: mm) taken on stem disks collected at breast height, as reported by Tomé et al. (2006);
2. Additional dbh measurements (unit: cm) from sites described in Table 1;
3. tree biomass measurements (unit: kg) made according to the methodology of Paulo and Tomé (2008) from sites described in Table 1.

We excluded trees with very high growth measurements, perhaps resulting from unrepresentative favorable conditions. The abnormal growth of these trees could also result in problems with establishing tree age through the counting of tree rings as some rings may have resulted from 2 years of continuous growth. Nevertheless, these data are still presented in the graphical results for transparency.

The carbon storage calculations are primarily based on the prediction of the aboveground tree biomass. The modelled responses of cork oak to solar radiation and water were established using tree biomass measurements from (1) high density (304 trees ha<sup>-1</sup>) stands with a high site index, (2) medium density (140 trees ha<sup>-1</sup>) stands at a low site index and (3) isolated trees with access to water. Because soil information was unavailable for the first and second datasets, it was assumed that the high stand density experienced lower resource availability due to higher

**Table 1** Location and characteristics of the stands used for (a) additional diameter measurements to Tome et al. (2006) and (b) biomass validation in YieldSAFE

Site name	Used to validate	Latitude (N)	Longitude (W)	Stand density (trees ha <sup>-1</sup> )	Nr of trees	Details
Cabeção	biomass	38.9541	8.0727	304	5	High stand density, high site index
Contenda	Biomass	38.0378	7.0648	140	6	Medium stand density, low site index
Vila Velha de Rodão	Biomass, dbh	39.6675	7.5378	100	10	Low stand density, high site index
Odelouca (a)	Biomass, dbh	37.3451	8.3782	Isolated tree	1	Nearby small river
Odelouca (b)	Biomass, dbh			Isolated tree	1	Away from water

tree competition. In this indirect way, we could predict lower and higher tree biomass for higher and lower stand density respectively.

Initial estimates of the model parameters were derived from an extensive literature review and existing tree measurements (Table 2). A Microsoft Excel© implementation of the model was used (Graves et al. 2010) and set up with a generated climate dataset built with Cligen 5.2 (Lane and Nearing 1995) based on reference data from a weather station in Southern Portugal (Évora, GDS 2005).

The first step of the model calibration was completed by “switching off” the water module, simulating a no limitation of soil water (see details in Graves et al. 2010). During this stage, the value of tree parameters unrelated to the constraints of soil water were “fine-tuned” so that the tree height, dbh and biomass outputs matched those for well-watered trees.

However in practice, water availability limits cork oak growth in Mediterranean environments (AFN 2010). Hence the second step was to “switch on” the water module, and to modify water-related parameters (gammat, pFCrit, PWPt) so that the modelled tree yields matched those of measured oak trees under severe water stress. This lower bound of growth was set assuming a soil with low soil water holding capacity (60 mm), which would be typical of a coarse textured soil (Wösten et al. 1999) with a depth of 15 cm.

### Modeling scenarios

The YieldSAFE model predicts above-ground biomass. In order to estimate the below-ground carbon sequestration, we assumed a root-to-shoot ratio (RSR) of 0.43 (Pereira et al. 2010). Carbon was estimated as 48 % of

the total tree biomass (aboveground + belowground) as suggested by IPCC (IPCC 2006). Therefore, carbon sequestration ( $C_{seq}$ ) is estimated as (Eq. 1):

$$C_{seq} = 0.48(B_t + 0.43 \cdot B_t) \quad (1)$$

where  $B_t$  is aboveground tree biomass (kg ha<sup>-1</sup>) predicted by the Yield-SAFE model.

An advantage of using a process-based model is the ability to predict growth in different soil water conditions. By combining different levels of planting in different modeling scenarios, it can be possible to understand the potential avenues by which cork oak planting could contribute to carbon sequestration.

Four implementation scenarios of 10, 30, 50, and 70 % of the available agricultural land being for used for cork oak agroforestry were investigated.

Typical advised tree densities for a modern agroforestry system are between 70 and 120 trees ha<sup>-1</sup> (Liagre and Dupraz 2008). We considered a hypothetical SAF system of 113 trees ha<sup>-1</sup> with a thinning of 63 trees ha<sup>-1</sup> at year 20 to reach the final density of 50 trees ha<sup>-1</sup>. This density and rotation can be considered to simulate a 40 m × 2.5 m design thinned to 40 m × 5 m, always allowing cropping between the tree rows (kept constant at 40 m) with a wide alley to allow wide machinery such as crop sprayers. This final density is similar to that traditionally suggested for Montados management by Natividade (1950).

Although other tree densities and designs may be explored to evaluate crop combinations or crop rotations (Graves et al. 2010), it is assumed that the annual crops had minimal effect on the growth of trees such as cork oak or holm oak (Graves et al. 2007) and would not change the magnitude of the carbon storage by trees. For the analysis we assumed a constant crop

**Table 2** Parameter set for *Q. suber* L. used in YieldSAFE

Parameter	Description	Value	References
Pheight	Pruning height (m)	3	Serrada et al. (2008) and data collection
Pbiomass	Proportion of biomass removed per prune	0.17	
Pshoots	Proportion of shoots removed per prune	0.2	
maxPropbole	Maximum proportion of bole	0.6	Data collection (Table 3)
Bheight	Maximum bole height (m)	6	
nShoots <sub>0</sub>	Initial number of shoots	1	Almeida et al. (2005)
Biomass <sub>0</sub>	Initial tree biomass (g)	12	
LA <sub>0</sub>	Initial tree leaf area (m <sup>2</sup> )	0.0174	
Ap	Power function to describe relationship between tree height and diameter	0.63	Burgess et al. (2004)
Epst	Radiation use efficiency (g MJ <sup>-1</sup> )	0.21	Faria et al. (1998)
F	Form factor of the tree	0.6	Data collection (Table 3)
gammat	Water needed to produce 1 g of tree biomass (m <sup>3</sup> g <sup>-1</sup> )	0.0004	Faria et al. (1998)
kt	Radiation extinction coefficient	0.8	Burgess et al. (2004)
Kmain	Maintenance coeficiente	0.0001	
LA max	Maximum leaf area (m <sup>2</sup> )	500	Data collection (Table 3)
ratiobranch	Ratio of branches to total biomass	0.23	
ratiothimber	Ratio of timber to total biomass	0.5	
Wood density	Wood density (g m <sup>-3</sup> )	710,000	Carvalho (1996)
pFcritt	Critical pF value for tree (log(cm))	3.5	Burgess et al. (2004)
PWPt	Permanent Wilting Point for Trees (log(cm))	4.2	
dsigma/density	The change in Sigmaheight with density	0.63	
Sigmaheight	Ratio of tree height to tree diameter for a free growing tree	17.69	Data collection (Table 3)
Canopywidth/depth	Ratio of maximum width to canopy depth	1.2	

rotation of wheat–wheat–fallow, as used under traditional agroforestry systems in Portugal.

Hence in summary the carbon storage potential of cork oak on identifiable available land was predicted using the YieldSAFE model and assuming (1) a hypothetical agroforestry system, (2) four levels of implementation on the available arable land and (3) two levels of soil water holding capacity.

## Results and discussion

Estimation of target areas where new agroforestry plantations could be developed

According to the maps produced by Natividade (1950), Blanco et al. (1997) and the European Forest Genetic Resources Programme (EUFORGEN 2009), cork oak can grow at any location in Portugal. However, this is neither consistent with the edapho-

climatic thresholds presented in literature, nor with the Portuguese ecological chart for cork oak (1984). The cork oak potential distribution map that we developed (Fig. 1c—grey), by overlaying maps of Fig. 1a, is broadly similar to distribution maps for the same species produced by APA (1984) and AFN (2010) although the spatial distribution is restricted because of the thresholds used. This cork oak potential spatial distribution was then intersected with available arable land (Fig. 1b). The overlay of these two spatial distributions shows that about 353,000 ha, mostly in the southwest, could potentially implement modern cork oak SAF systems (Fig. 1c—black).

YieldSAFE calibration and validation to predict biomass growth

The calibration process produced a parameter set presented in Tables 2 and 3. All the parameters were found in the literature or were derived from existing



**Fig. 1** **a** Source datasets with tree distribution limiting thresholds; **b** rain-fed arable land; **c** potential tree distribution for *Q. suber* L. (grey + black 2355,600 ha) on rain-fed arable land (black 353,000 ha)

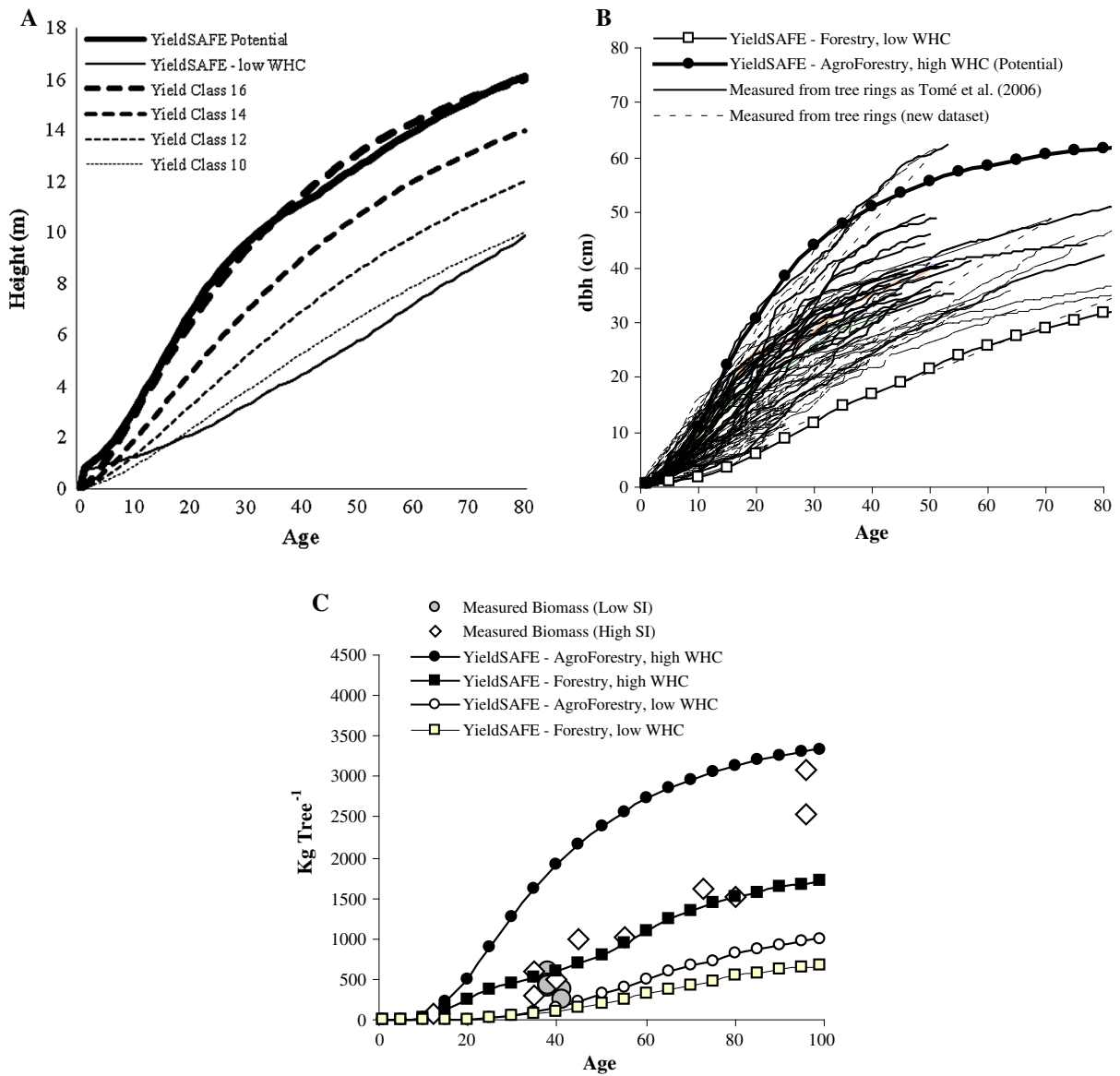
data measurements confirming the ease of using YieldSAFE.

Using these parameters and assuming two contrasting soil water capacity profiles it was possible to achieve outputs similar to existing models for height growth and measurements of diameter and biomass.

Comparing the tree height curve produced by YieldSAFE with the dominant height curves proposed

by Sanchez-Gonzalez et al. (2005), we observe that YieldSAFE predicts a similar range of minimum and maximum heights: 8–16 m respectively at age 80 (Fig. 2a). The predictions of dbh also matched the range of measurements of dbh established from the tree rings (Fig. 2b).

Although there are few data on measured biomass in cork oak Montado trees (tree cuts are forbidden by



**Fig. 2** Potential and water reduced growth calibration results of YieldSAFE for **a** tree height vs Yield Classes from Sanchez-Gonzalez et al. (2005), **b** diameter at breast height (DBH) vs tree

ring measurements from Tome et al. (2006) and new measurements and **c** predicted versus measured tree biomass from low and high site indices (S)

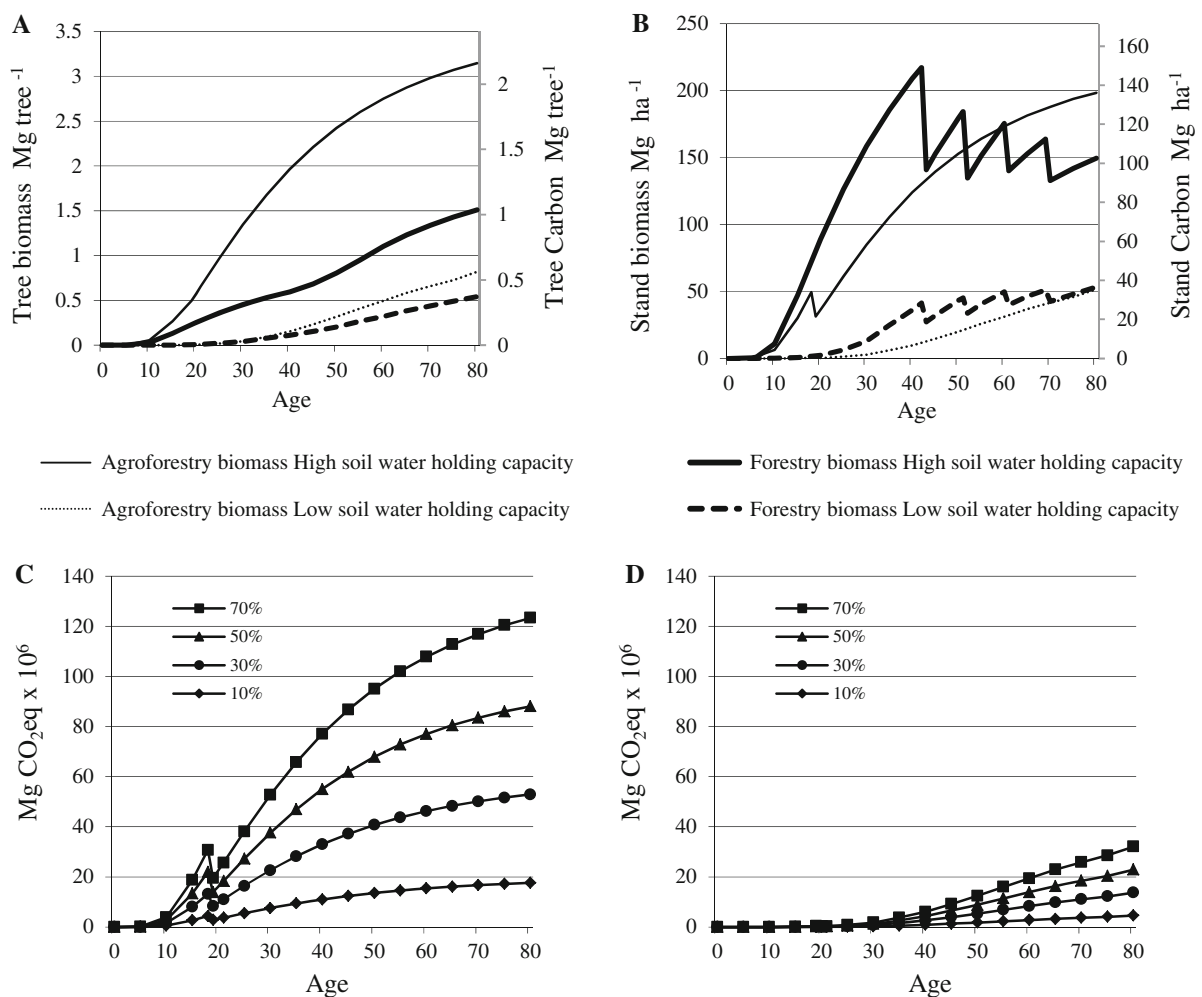
Portuguese law), our existing measurements indicated that trees can weigh about 3 tons at year 96 (Fig. 2c). These measurements are higher than the maximum of 2 tons reported by Montero et al. (2005) for the Spanish “alcornocales” (cork oak forests). The tree density in the “alcornocales” may be greater than 800 trees ha<sup>-1</sup> (e.g. Calzado and Torres 2013) and therefore greater inter-tree competition will constrain the growth of an individual tree.

### Modeling scenarios

The widely spaced agroforestry design of 113 trees ha<sup>-1</sup> with a thinning of 63 trees ha<sup>-1</sup> at year 20 minimises the competition between trees and hence the growth of individual trees will tend to be larger than in forestry stands (Fig. 3a). Ratios of agroforestry tree size to forestry tree size of up to 1.4 have also been observed by Balandier and Dupraz (1998), Cabanettes et al. (1998)

**Table 3** Source for some parameters of Table 2, based on data collection

Parameter	Number of tree samples	Minimum	Average	Maximum	SD
maxPropbole	2,025	0.08	0.26 <sup>a</sup>	0.93	0.09
Bheight	3,008	0.7	2.38	6.00 <sup>a</sup>	0.76
F	26	0.20	0.60 <sup>a</sup>	1.20	0.29
LA max	26	6.20	128.18	500.00 <sup>a</sup>	93.28
Ratiobranch	26	0.08	0.23 <sup>a</sup>	0.44	0.09
ratiotimber	26	0.30	0.50 <sup>a</sup>	0.74	0.12
Sigmaheight	1,004	8.48	17.69 <sup>a</sup>	33.07	3.94
Canopywidth/depth	26	0.53	1.2 <sup>a</sup>	2.38	0.5

<sup>a</sup> Parameter for the Yield-Safe model (in Table 2)**Fig. 3** Comparison of YieldSAFE estimates for aboveground biomass and total carbon (above + belowground) at tree (a) and stand level (b) for *Q. suber* L. under forestry and agroforestry systems under different soil water holding capacity. c, d Thesequestration (in  $\text{CO}_2\text{eq}$ ) for different agroforestry implementation scenarios (10, 30, 50 and 70 %) of the available 353,000 ha of arable land (see Fig. 1) under c high and d low soil water holding capacity



and Graves et al. (2007). However, our biomass measurements, although scarce, indicate that trees may reach ratios up to 2 when competition is low and water resources are available (Fig. 2c).

The model predicts that after 80 years of growth, an individual tree can store between 0.4 and 2.2 Mg C. At the stated tree density this corresponds to 35–136 Mg C ha<sup>-1</sup> (Fig. 3a, b). The model also predicts that the carbon content of the mature trees in an agroforestry system can be greater than in a forestry stand that has been regularly thinned (Fig. 3b). For example more carbon could be stored in the trees of an 80 year old agroforestry stand (with 50 trees ha<sup>-1</sup> on a soil with a high water holding capacity) than in the trees of a thinned forest with 58 % tree canopy cover as suggested by Natividade (1950).

Traditionally, land managers allocate the ‘poor’ areas to forestry and good areas to agricultural crops. The modelled results indicate that on farm land with a high water holding capacity, it is possible maintain food production (as it is an agroforestry system) and achieve higher rate of carbon sequestration in the trees than in the trees of a forest on poorer land (Fig. 3b).

The procedure in this paper allows the prediction of how the interacting effects of soil type and tree planting method affect carbon sequestration. At present the Portuguese national forestry inventory does not distinguish between forestry and agroforestry, and hence it is not possible to estimate current carbon storage under agroforestry. The analysis shows that the potential carbon sequestration at year 80 ranges from  $5 \times 10^6$  Mg CO<sub>2</sub> if implemented on 10 % of available land with low water holding capacity (Fig. 3d) to  $123 \times 10^6$  Mg CO<sub>2</sub> if implemented on 70 % of available land with high water holding capacity (Fig. 3c). Any of the chosen scenarios in soils with high water holding capacity (Fig. 3c) can yield more carbon than any scenario under lower soil quality (Fig. 3d). For example an implementation of 10 % of agroforestry in areas with high soil water holding capacity (Fig. 3c) is predicted to yield approximately the same carbon as 50 % implementation in poorer agricultural land (Fig. 3d). Such analysis can guide policy makers who determine the type of financial incentives given to support carbon sequestration.

In 2012, Portugal had a deficit of  $2,739 \times 10^3$  Mg CO<sub>2</sub> sequestration regarding the target of the government program for creating new afforestation areas (MAODTR 2012). The results suggest that in the short

term (e.g. 10 years), this deficit could be addressed by establishing cork oak agroforestry systems on 50 % of the agricultural land (about 176,500 ha) with high water holding capacity ( $2,795 \times 10^3$  Mg CO<sub>2</sub> in year 10, Table 4). Although this research did not assess the

**Table 4** Mean annual Increments of CO<sub>2</sub>eq and cumulative storage (in tree biomass) for different ages at different implementation scenarios in the available arable land (353,000 ha)

Implementation scenarios % (area)	Mean annual increment (Mg CO <sub>2</sub> eq year <sup>-1</sup> ) × 10 <sup>3</sup>			Cumulative storage (Mg CO <sub>2</sub> eq) × 10 <sup>3</sup>	
	Age	Soil water holding capacity		Low	High
		Low	High		
10 % (35,300 ha)	10	0.3	56	3	559
	20	2	161	37	3,224
	30	8	251	254	7,537
	40	22	275	863	11,011
	50	35	272	1,771	13,577
	60	46	257	2,769	15,404
	70	53	238	3,693	16,693
	80	57	220	4,584	17,621
	30 % (105,900 ha)	10	1	168	9
20		5	484	110	9,672
30		25	754	761	22,612
40		65	826	2,590	33,033
50		106	815	5,312	40,730
60		138	770	8,308	46,213
70		158	715	11,079	50,079
80		172	661	13,753	52,863
50 % (176,500 ha)		10	2	280	16
	20	9	806	183	16,120
	30	42	1,256	1,269	37,687
	40	108	1,376	4,317	55,054
	50	177	1,358	8,853	67,883
	60	231	1,284	13,847	77,021
	70	264	1,192	18,465	83,465
	80	287	1,101	22,922	88,105
	70 % (247,100 ha)	10	2	391	22
20		13	1,128	257	22,568
30		59	1,759	1,776	52,762
40		151	1,927	6,044	77,076
50		248	1,901	12,394	95,037
60		323	1,797	19,385	107,830
70		369	1,669	25,851	116,851
80		401	1,542	32,091	123,346



spatially distribution of soil water holding capacity (due to lack of data at national scale) the predictions indicate that almost half of the present carbon storage deficit could be addressed in a 10 year frame (Table 4).

## Summary and conclusions

Existing maps of potential cork oak distribution for Portugal lack a concise description of how the boundaries were determined. This paper describes the production of a new potential distribution map for cork oak based on edapho-climatic thresholds, which can be updated in the light of future climate change. This map, intersected with arable land, spatially identified 353,000 ha available to implement cork oak based silvoarable agroforestry systems.

The studied scenarios with the YieldSAFE model predictions suggest that carbon storage by the trees of cork oak based silvoarable agroforestry systems could be 35–136 Mg C ha<sup>-1</sup> after 80 years. Depending on the upscale implementation scenario, the net effect could be  $5 \times 10^6$  Mg CO<sub>2</sub> after 10 years or  $5$  to  $123 \times 10^6$  Mg CO<sub>2</sub> in 80 years.

The model predicted that after 80 years, the carbon stored by the standing trees in a silvoarable system could be greater than those in a conventional forest system. In terms of carbon sequestration by the trees on a soil with high water holding capacity, it appears preferable to plant agroforestry systems on the best agricultural land, instead of planting forests on poor agricultural land. Such an approach would also allow farmers to maintain food production.

The understanding of such dynamics becomes important as pressure on agricultural land increases (Schroter et al. 2005). Agroforestry allows the multiple use of land with higher resource efficiency (Graves et al. 2007) and higher environmental benefits than monocultures (Palma et al. 2007a, b). The development and use of models, such as YieldSAFE, combined with assessment of land quality and climate data allows the prediction of tree carbon stocks for different tree systems (Miranda et al. 2002; Pereira et al. 2006). In addition to the carbon storage benefits reported here, agroforestry with cork oak or holm oak is considered to have high environmental and landscape value (Joffre et al. 1999; Pinto-Correia 1993, 2000; Plieninger and Wilbrand 2001). Hence there is a logic to using these species for carbon sequestration.

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